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General Aviation Maintenance- Related Accidents: A Review of Ten Years of NTSB Data

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16. Abstract NTSB accident investigation reports for general aviation accidents occurring between 1988 and 1997 were analyzed in order to provide a descriptive look at ten years worth of accident data. This sample included 1,503 reports, all of which indicated at least one maintenance-related issue as a cause or factor in the accident. Initial analyses describe the frequency of occurrence for type of maintenance task and type of aircraft. Accidents were compared on frequency of occurrence, number of fatalities, and number of serious injuries. Odds for each variable resulting in a fatality or injury are reported. Results indicated that installation errors were the leading maintenance-related cause or factor involved with the accidents. Since installation errors were most common further analyses focused on a more detailed description of installation error. Type of installation error, type of aircraft system involved in the installation, whether or not the installation was inspected, credentials of the mechanic performing the installation, and the operational impact of the installation error were investigated. Results indicate that reversed installation and wrong part were the two installation errors most likely to cause death or injury in GA aircraft accident.			
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GENERAL AVIATION MAINTENANCE-RELATED ACCIDENTS: A REVIEW OF TEN YEARS OF NTSB DATA

During the last several decades, improvements in aviation safety have made commercial flying in the United States the safest form of transportation. General Aviation (GA), however, has not enjoyed the same safety record. From 1988 to 1997, the average rate of accidents per 100,000 flight hours was 8.172 for GA and .2267 for scheduled commercial airlines operating under 14 CFR 121 (NTSB, 2000a). Although GA aircraft log almost twice as many flight hours as do the airlines (for 2000: 30,800,000 and 17,170,000, respectively [NTSB, 2000b,c]), the accident rate per 100,000 flight hours for GA aircraft in 2000 is over twenty times greater than the rate for commercial aircraft (5.96 and .285, respectively, NTSB, 2000b,c). To further delineate the differences in safety between GA and commercial airlines, from 1988-1997 commercial airline accidents resulted in 1,493 fatalities (NTSB, 2001b) while GA accidents accounted for 7,446 fatalities (NTSB, 2001c).

Historically, GA human factors research has placed greater emphasis on the behavior of the pilot, his/her judgment and decision making, and interactions with air traffic control while paying limited attention to the maintenance environment. Often, GA maintenance accident investigations end with the conclusion that the cause of an accident was maintenance-related- without further investigating the details of who performed the maintenance, why the maintenance was necessary, and any possible human factors issues underlying the maintenance error. Consequently, no comprehensive database of GA maintenance-related human factors incident data exists, and little information has been published in the scientific literature regarding human factors issues in GA maintenance operations.

While the literature regarding GA aviation maintenance human factors is rather anemic, recent studies have helped to identify the severity of human error in aviation maintenance. Maintenance-related errors have been associated with up to 15% of major aircraft accidents (Murray, 1998) and 16% of Naval Aviation Class A Flight Mishaps (Schmidt, Schmorow, & Hardee, 1998). Despite this seemingly small percentage, Allan and Marx (1993) found that maintenance errors are the second leading cause of fatal accidents in aviation, exceeded only by pilot error. These statistics, coupled with the relative age of the fleet of GA

aircraft, as well as predictions of increased air traffic, suggest a strong need for a more complete understanding of the human factors issues in GA maintenance.

Due to recent interest in maintenance human factors in Part 121 and 135 operations, several important issues relevant to human performance in the maintenance environment have been discussed. For example, Reason (1998) suggests that outdated maintenance schedules should be modified to prevent unnecessary human contact with the aircraft system. Due to technological advances, aircraft components have become more reliable and, as such, require less-frequent "disassemble and inspect" methods of maintenance that can often do more harm than good. In this case, the human introduces risk in the form of human error, which may not be justified for what might be only a marginal increase in safety.

The current study provides an overview of a ten-year sample of GA maintenance-related accident data obtained from the National Transportation Safety Board (NTSB) GA accident investigation reports. Initially, we present a comparison of GA fatal-accident rates with GA maintenance-related fatal accident rates. The frequency and severity (measured in fatalities and injuries) of maintenance activities determined to be a cause or factor in these accidents are also presented. Initial analyses indicated that maintenance installation was cited in enough investigation reports (20%) to warrant a closer examination. Therefore, the second phase of this study focused only on accidents involving maintenance installation in this sample. Frequency of the type of aircraft system involved in installation, the type of installation error, who performed the installation, and the operational result of the error were calculated. The odds of a fatality or injury for each type of installation error and aircraft system are presented as a measure of the risk.

METHOD

GA Accident Data

Final reports for all maintenance-related accident investigations involving GA aircraft between 1988 and 1997 were obtained from the NTSB. The NTSB defined GA aircraft as "all civil flying except revenue air carrier (including all Part 121 and all Part 135 operations"; S. Smith, personal communication, May 16, 2000). The current sample of accident reports was obtained by querying the NTSB database for accidents that included

either a maintenance subject code or a maintenance personnel code. The NTSB defines an accident as "an occurrence associated with the operation of an aircraft that takes place between the time any person boards the aircraft with the intention of flight and all such persons have disembarked, and in which any person suffers death or serious injury, or in which the aircraft receives substantial damage" (NTSB, 2001d). This study included only NTSB accident reports; incidents were excluded. Of the 20,884 NTSB General Aviation accident investigation reports available between 1988 and 1997, 1,474 (7.1%) reported at least one maintenance-related error as a primary cause or factor in the accident.

Part 1: GA Accident Overview

Data Classification. NTSB accident reports categorize maintenance activities according to the following taxonomy: maintenance, service of aircraft equipment, inspection, compliance with Airworthiness Directive (AD), annual inspection, adjustment, alignment, installation, lubrication, modification, replacement, major repair, major alteration, service bulletin/letter, design change, overhaul, major overhaul, and rebuild/remanufacture. The NTSB identifies *type of aircraft* as follows: airplane, helicopter, glider, balloon, blimp/dirigible, ultralight, and gyroplane.

Analyses. The frequency of types of maintenance activity, maintenance personnel, and type of aircraft are the primary focus of the analysis. Categories are compared based on frequency as well as number of fatalities and injuries.

Part 2: Installation Errors

Each of the 295 installation reports were reviewed and coded by two researchers. A separate taxonomy was developed for each variable of interest and discrepancies in coding were mediated by discussion. The focus of this study was to analyze the frequency of each error and aircraft system occurring in this 10-year sample. Of additional interest was the operational impact of the accident and whether or not the AMT was properly certified.

Installation Error Classification. The error classification utilized for this analysis was adapted from Graeber and Marx's (1993) installation error taxonomy. Categories of installation error included wrong part, reversed installation, incorrect attachment, omission, and incorrect connection. *Wrong part* refers to the installation of a part that does not comply with the manufacturers specifications or any supplemental service bulletins. The *reversed installation* category refers to the installation of aircraft components that are cross-connected or reversed. *Incorrect attachment* refers to improper installation of

parts that have the sole function of attaching two or more components of the aircraft (e.g., nuts, bolts, washers, brackets and harnesses). *Omission* refers to an installation that did not include a required component. *Incorrect connection* refers to installations of aircraft components that serve a function beyond simply attaching two or more parts of the aircraft. An example of an *incorrect connection* would be a fuel line that is accidentally crimped during installation. Although the fuel line does attach the fuel tank to the fuel intake system, the fuel line also has the additional function of transporting fuel between the fuel tank and the fuel intake system.

Aircraft System Classification. The aircraft system taxonomy adapted and modified the NTSB aircraft system classifications (1998) used to code the system implicated in the accident under investigation. The aircraft system categories are: flight controls, powerplant, landing gear, flight/navigation instruments, electrical system, fuselage, rotor system, wing (vertical and horizontal), fire warning system, AC/heat/pressurization/oxygen, and anti-ice/de-ice system.

Certified Mechanic. Each report was coded to indicate whether the personnel who performed the installation on the accident aircraft was a licensed Airframe and Powerplant (A&P) mechanic. Only two categories were utilized; *certified mechanic* and *non-certified mechanic*.

Operational Impact. To determine operational impact, a taxonomy developed by Veinott and Kanki (1995) was utilized. This taxonomy categorizes accident outcomes based on whether the aircraft was flown to the intended destination, returned to the departing airport, or made an emergency landing.

Analyses. Frequency of each installation error, aircraft system, and operational impact are reported. Contingency tables were constructed and the odds of each category resulting in a fatality or injury were calculated to compare risk. A chi-square analysis was performed to determine if type of error, type of system, presence of a certified mechanic, and operational impact were statistically independent of the presence of a fatality or injury. Cramer's V is reported with all significant chi-square analyses to indicate the strength of association.

RESULTS

Part 1: GA Accident Overview

Table 1 presents the frequency of accidents for each type of aircraft. Airplanes were involved in more maintenance-related accidents than any other type of aircraft ($n = 1,262$; 85.7%). Helicopters were the next most frequently occurring aircraft in this sample with 182 (12.4%) involved in maintenance-related accidents. Less than 2% of the maintenance-related accidents involved

Table 1

Frequency of Type of Aircraft Involved in a Maintenance-Related Accident, 1988-1997.

Type of Aircraft	Frequency	Percent
Airplane	1,262	85.7
Helicopter	182	12.4
Glider	9	0.6
Balloon	7	0.5
Gyroplane	7	0.5
Blimp/dirigible	3	0.2
Ultralight	2	0.1
Total	1,472	100.0

other types of GA aircraft. The number of maintenance-related accidents and fatalities per year are provided in Table 2. The year with the highest number of maintenance-related accidents (1989, $n = 176$) also accounted for the most fatalities ($n = 84$). The next highest year was 1992, with 73 fatalities resulting from 151 maintenance-related accidents.

Figure 1 depicts the ten-year trend of the percentage of accidents that result in a fatality for all GA accidents compared with maintenance-related accidents. The percentage of all maintenance-related accidents that involved a fatality was quite variable across the ten-year time frame, with peaks observed in 1989 and 1994 when

Table 2

Number of Maintenance-Related Fatalities and Accidents by Year.

Year	Fatalities	Accidents
1988	21	132
1989	84	176
1990	34	146
1991	54	160
1992	73	151
1993	39	123
1994	52	122
1995	48	134
1996	51	159
1997	48	171
Total	504	1474

27% and 22% (respectively) of all maintenance-related accidents resulted in fatalities. The year with the lowest percentage of maintenance-related accidents resulting in a fatality was 1988 (13%). Fourteen percent of all maintenance related accidents in 1997 were fatal. Fatalities occurred, on average, in 18% of the maintenance-related accidents annually.

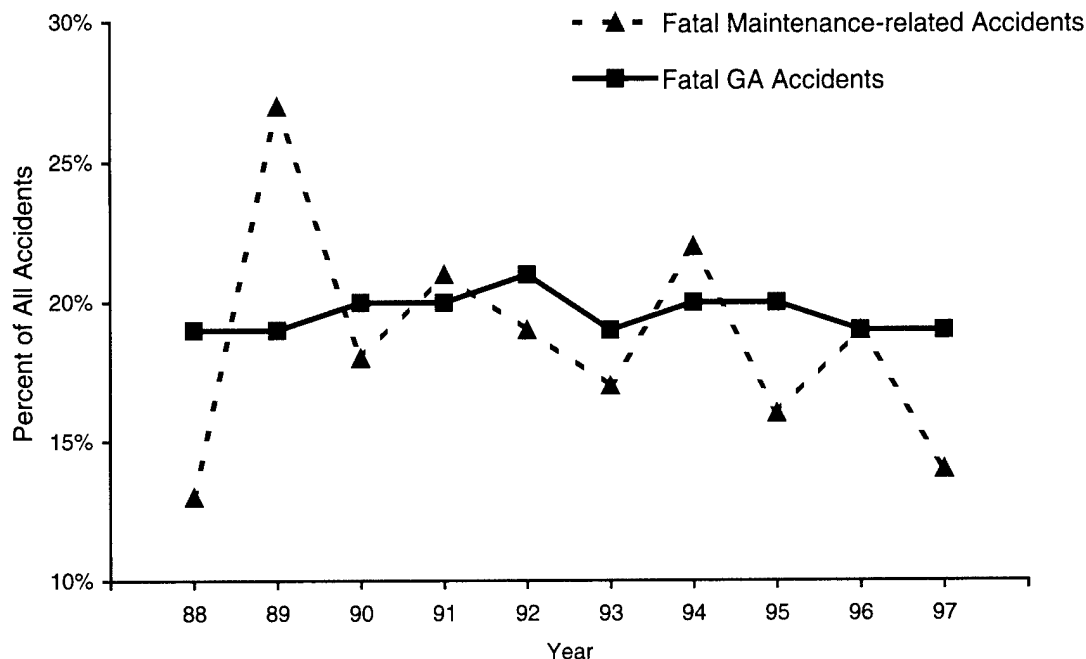


Figure 1. Percent of All Accidents That are Fatal: All GA Accidents Compared With Maintenance-Related Accidents.

Type of Maintenance Activity. Table 3 presents the frequency and percent of each maintenance activity identified as a cause or factor in the NTSB accident reports.

Of the 1,474 NTSB maintenance-related GA accident reports analyzed, 295 (20.0%) cited installation as a primary cause or factor in the accident. The next three most frequently occurring maintenance activities included maintenance (n = 217, 14.7%), maintenance inspection (n = 202, 13.7%), and annual inspection (n = 124, 8.4%). Maintenance activities that accounted for less than 4% of the total were combined into the *Other* category. Some of these maintenance activities include compliance with an AD, replacement, major repair, design change, and major overhaul. As a result of the method in which the sample was obtained, some reports contained NTSB subject codes that were not "maintenance" codes. These are included in Table 3 as *Non-maintenance*.

Figure 2 presents the number of fatalities and non-fatal injuries for each maintenance activity. Installation problems were not only the most frequently cited maintenance issue; they also resulted in the most severe consequences. Accident reports citing installation problems accounted for 100 fatalities

Table 3

Frequency of Maintenance Activity for all GA Maintenance-Related Accidents

Maintenance Activity	Frequency	Percent
Installation	295	20.0
Maintenance	217	14.7
Maintenance Inspection	202	13.7
Annual Inspection	124	8.4
Service of Aircraft	91	6.1
Adjustment	82	5.5
Modification	62	4.2
Overhaul	59	4.0
Other	312	21.1
Non-maintenance ^a	30	2.0
Total	1,474	100.0

^a Non-maintenance refers to codes used in the NTSB accident reports that are not labeled as "maintenance." Some examples include landing gear, tailwheel lock, flight manuals, and radar assistance to VFR aircraft.

and 210 injuries. Installation problems, maintenance, and maintenance inspection accounted for over 50% of the fatalities in this sample.

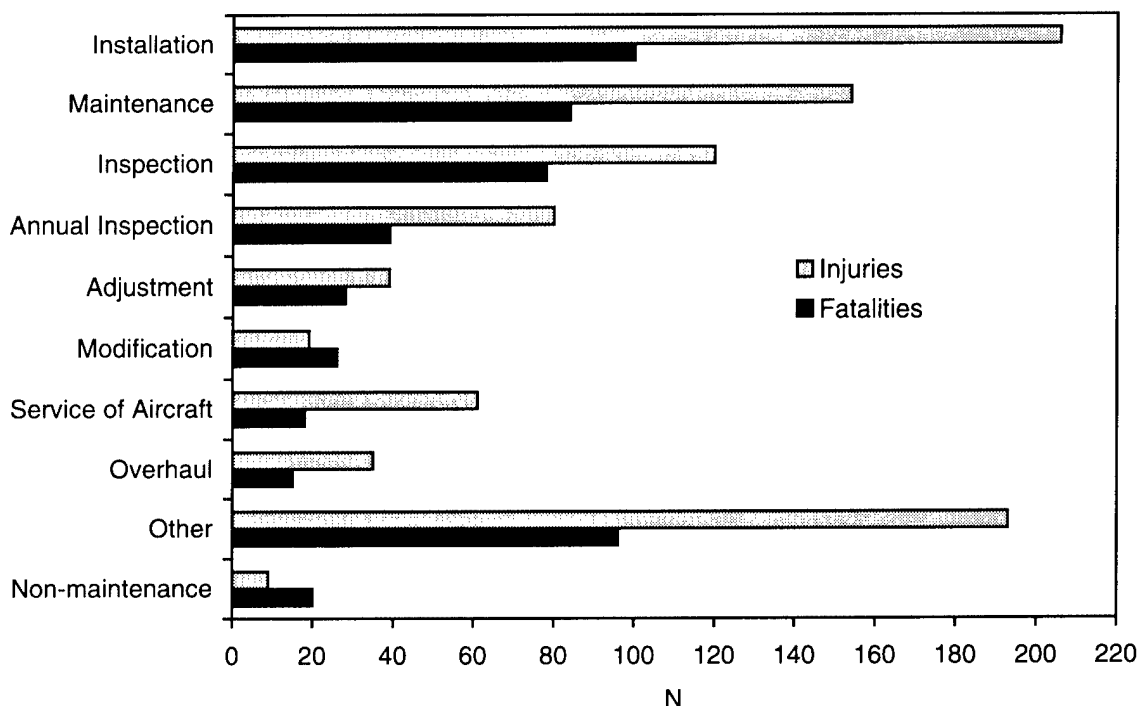


Figure 2. Total Fatalities and Injuries by Type of Maintenance Activity for GA Maintenance-related Accidents From 1988 to 1997.

Part 2: Installation Errors

Fatality or Injury. One hundred twenty-two (41%) of the 295 installation accident reports cited no injuries or fatalities. One hundred seventy-seven accident reports (59%) cited injuries, fatalities, or both.

Type of Error. Table 4 presents the frequency and percentage for each type of installation error. Table 5 presents the odds for each type of error resulting in a fatality or injury. Two hundred ninety cases contained sufficient information to supply a valid code for *Type of error*. Five reports did not include enough information to classify type of installation error; these cases were excluded from analysis. Incorrect attachment was the most

frequently occurring type of installation error in this sample, $n = 83$. Installing the wrong part, however, resulted in a greater likelihood of injury. This type of error was 1.882 times more likely to result in a fatality or injury than to result in no fatality or injury. Omitting a component during the installation was the third most frequently cited installation error in this sample ($n = 63$). While the odds of an installation error producing an injury or fatality range from 1.882 for installation of a wrong part to 1.172 for an omission, the presence or absence of a fatality or injury was not statistically dependent on the type of installation error, $\chi^2(4, N = 288) = 1.83, p > .05$.

Table 4

Installation Accidents: Frequency and Percent for Type of Error, Type of System, Inspected On time, Certified Mechanic, Operational Impact, and Fatality or Injury.

Installation Variable	Level	Frequency	Percent
Type of Error	Incorrect Attachment	83	28.6
	Incorrect Connection	64	22.1
	Omission	63	21.7
	Wrong Part	49	16.9
	Reversed Installation	29	10.0
	Total	290	97.3
Type of System	Powerplant	163	56.2
	Flight Controls	39	13.4
	Landing gear	30	10.3
	Rotor System	31	10.7
	Electrical System	15	5.2
	Wing	6	2.1
	Fuselage	3	1.0
	Flight/Navigation Instruments	3	1.0
Certified Mechanic	Total	290	99.9
	Yes	31	91.2
	No	3	8.8
Operational Impact	Total	34	100.0
	Emergency Landing	253	85.8
	Fly to Destination	32	10.9
	Return to Departure Airport	9	3.1
Fatality or Injury	Total	294	99.8
	Yes	175	59.3
	No	120	40.7
	Total	295	100.0

Table 5

Installation Accidents: Crosstabulation and Odds for Fatality or Injury by Type of Error, Type of System, Certified Mechanic, and Operational Impact.

Installation Variable		Level	Fatality or Injury Involved?		
			Yes	No	Odds
Type of Error	Incorrect Attachment		50	33	1.515
	Incorrect Connection		36	28	1.285
	Omission		34	29	1.172
	Wrong Part		32	17	1.882
	Reversed Installation		18	11	1.636
	Total		171	119	1.436
Type of System	Powerplant		101	62	1.629
	Flight Controls		27	12	2.250
	Rotor System		16	15	1.066
	Electrical System		11	4	2.750
	Landing gear		5	25	0.200
	Wing		6	0	0.000
	Flight/Navigation Instruments		3	0	0.000
	Fuselage		1	2	0.500
		Total	170	120	1.416
Certified Mechanic	Yes		19	12	1.583
	No		1	2	0.500
	Total		20	14	1.428
Operational Impact	Emergency Landing		165	88	1.875
	Fly to Destination		7	25	0.280
	Return to Departure Airport		2	7	0.285
	Total		174	120	1.450

Type of System. Table 4 presents the frequency and percentage for each type of aircraft system involved in the installation procedure. Table 5 presents the odds of an installation error for each type of system resulting in a fatality or injury. Two hundred and ninety cases contained enough information to assign a code for type of aircraft system. The remaining five cases were excluded from analysis. The largest proportion of errors were committed during powerplant installations ($n = 163$, 56.2%). Installation errors associated with the flight controls were the second most frequent category of aircraft systems ($n = 39$, 13.4%). Installation errors on the electrical system

were reported in 15 (5.2%) of the accidents. Only three reports (1.0%) cited installation errors on the flight/navigation instruments.

While powerplant installations were a cause or factor in over half of the accidents in this sample, installation errors on the flight controls or electrical system were more likely to result in an injury or death (odds = 2.250 and 2.750, respectively). The odds of an installation error producing an injury or fatality ranged from 0.200 for an installation error on the landing gear to 2.750 for installation errors on the electrical system. Chi-square analysis on the type of system by fatality or injury *versus* no fatality or injury

cross tabulation resulted in a significant test of independence $\chi^2(7, N = 290) = 33.43, p < .005$. Cramer's V coefficient was also significant, $\phi_c = .340, p < .005$. Thus, the presence of a fatality or injury is statistically dependent on the type of aircraft system involved in the installation error. The significant Cramer's V coefficient suggests a moderately strong relationship between fatality or injury and type of aircraft system.

Certified Mechanic. Only 34 out of the 300, or 11.3%, of the installation accident reports indicated whether a certified mechanic performed the installation work. Of these 34, 31 (10.3%) verified that a certified mechanic performed the installation. Three cases reported that the mechanic performing the installation was not certified. Two hundred sixty-six cases were coded with a missing value. A chi-square analysis was not performed due to the small cell sizes.

Operational Impact. Table 4 presents the frequencies for the operational impact categories. Two hundred ninety-four reports contained sufficient information to assign a value for operational impact. In the vast majority of the cases (85.8%), the pilot had to execute an emergency landing. Only nine (3.1%) of the aircraft were able to return to the departure airport. Thirty-two (10.9%) of the aircraft were successfully flown to the intended destination.

Table 5 presents the odds of the operational impact resulting in a fatality or injury. Aircraft returning to the departure airport after experiencing an in-flight problem greatly reduced the chance of a fatality or injury (odds = 0.285) as did aircraft flying to the intended destination (odds = 0.280). Aircraft making an emergency landing were 1.81 times more likely to produce a fatality or injury than no fatality or injury. The chi-square analysis for operational impact by fatality or injury *versus* no fatality or injury was significant at $\chi^2(2, N = 294) = 27.34, p < .005$. Cramers V coefficient was also significant, $\phi_c = .305, p < .005$.

DISCUSSION

Recent studies that have assessed the frequency of maintenance-related commercial, naval, and GA accidents have found an accident rate close to 20% (see Murray, 1998; Schmidt, Schmorow, & Hardee, 1998). The current study found that 7.05% of all GA accidents occurring between 1998 and 1997 were attributed to a maintenance-related cause or factor. Due to the method used to obtain the sample in this study, the authors believe that 7.05% is a conservative estimate of GA maintenance-related accidents during

this period. NTSB accident investigators report the probable cause of an accident with a subject code. NTSB accident reports that contain a subject code not classified as a maintenance code (e.g., "22000-Landing Gear") would not have been included in this sample but may have been involved in a "maintenance-related" accident. As a result, there are probably many more maintenance-related accident reports in the NTSB Database that were not included in this study because they were not designated with a maintenance code.

The most frequently occurring maintenance activity in this sample was *installation*. Accident reports that identified *installation* as a cause or factor accounted for more fatalities than any other maintenance activity. *Maintenance* and *maintenance inspection* were the second and third (respectively) most frequent maintenance activities. In addition, *installation*, *maintenance*, and *maintenance inspection* accounted for more than 50% of the fatalities in this sample. Since *installation* is the most ubiquitous maintenance activity (most maintenance activities could be described as an "installation"), rigorous study of the underlying human behavior is needed. The various categories associated with installation errors (incorrect attachment, omissions, wrong parts, etc.) suggest that the human factors of these events may span a broad range of concerns. For example, omissions may involve attentional lapses, distractions, complex installation instructions, or incomplete training. To better understand the importance of these other human factors, more extensive data are needed regarding the specific maintenance activities. Future studies could look at the behavioral and cognitive factors involved in the day-to-day successful execution of installation procedures.

Maintenance inspection is typically the last line of defense in an aircraft maintenance operation. Maintenance inspections and annual inspections together were cited in 22% of the fixed-wing accidents. Thus, it is surprising that so little information is included in the accident reports concerning the maintenance and inspection history of each aircraft. Indeed, most of the reports in this sample contained no maintenance or inspection history at all. The effectiveness of current inspection practices is difficult to assess without a prior maintenance history. The relatively high frequency of accident reports citing inspection as a probable cause may suggest that the training GA inspectors receive—as well as the regulations guiding inspection practices—may need to be reevaluated.

The maintenance activity categorized as "Maintenance" is difficult to interpret due to the ambiguous name. The authors speculate that this code is used either to refer to routine maintenance activities (e.g., an oil change) or when the accident was determined to be maintenance-related, but information regarding the specific maintenance activity was not discovered during the course of the investigation. The ambiguity of this category of maintenance activity is somewhat troubling since it is the second most frequently cited maintenance activity in this sample.

Fixed-wing aircraft were involved in the majority of accidents (85.7%) from 1988-1997. This is not surprising since fixed-wing aircraft are the most common type of GA aircraft (in 1996, 86% of GA aircraft were fixed-wing airplanes; FAA, 1996). However, helicopters, which in 1996 comprised only 3% of GA aircraft (FAA, 1996), were involved in 12.4% of the maintenance-related accidents. Helicopters, which are already well known for their high maintenance requirements, may be especially prone to maintenance-related accidents. However, the type of maintenance activities reported as causal factors in this study were identical to those found for fixed-wing aircraft, installation and inspection. This suggests that the maintenance errors being committed are aircraft-independent and efforts to manage human error in installation and inspection could greatly increase safety for all types of aircraft. Other GA aircraft such as gliders, gyroplanes, balloons, and ultralights, comprised such a small portion of this sample that no conclusions could be made.

Maintenance installation errors such as reversed installation and omission have been cited in other studies (Graeber and Marx, 1993; Hobbs & Williamson, 2001) as common errors in the maintenance environment. The current study found that *incorrect attachment* and *incorrect connection* were the most frequent categories of installation errors in this sample. The distinction between a connection and an attachment may seem slightly ambiguous, but the underlying human behaviors may be quite different. For instance, an incorrect attachment could be the result of a lapse in concentration or incomplete documentation in the manual. An incorrect connection may occur because of damaging one part of an aircraft (e.g., a fuel line) while attempting to service another part of the aircraft. These differences may require separate strategies for study and intervention.

Installation of components can be required in any of the numerous aircraft systems, and some systems are more critical to safety than others. In fact, the

significant chi-square test for type of system by fatality or injury *versus* no fatality or injury suggests that the outcome of the accident (fatality or injury) is dependent on the type of system upon which the installation error was committed. Powerplant installation errors were the most prevalent in all accidents. This could be because of the central role played by the powerplant, its complexity, or other factors such as limited access to engine components inherent in aircraft design, particularly small aircraft. Although occurring less frequently, the odds of a fatality or injury increased when the installation error involved flight controls or the electrical system.

GA maintenance technicians must perform many different maintenance tasks across a wide array of aircraft types to keep them airworthy. Understanding which maintenance activities pose the greatest risk is crucial to developing an effective error management and prevention program. While we are not necessarily advocating the total adoption of Operational Risk Management (ORM) techniques as used by the military services (for example, see Air Force Pamphlet 90-902, 14 December 2000, available: <http://afpubs.hq.af.mil>), it seems reasonable to develop guidance to aid maintainers on the inherent risks of maintaining various general aviation aircraft. These guidelines could be empirically developed, informed by accident and incident event data. Thus, a comprehensive database of maintenance error data becomes crucial.

Marx (1997) has proposed that the aviation industry move towards 100% error reporting in maintenance. Marx's reasoning is that nearly every mechanical failure is investigated and archived so that the failure rate of a specific type of component can be analyzed and precisely tracked. However, the same investigative and analytical resources are not applied to cases of human error in the maintenance shop. Marx suggests that a major obstacle to 100% error reporting in maintenance is the punitive work environment so pervasive industry-wide. Many aviation maintenance technicians (AMTs) may hesitate to report their own errors for fear of reprisal from management or government. Therefore, any maintenance-error reporting system will likely require some level of immunity to disciplinary action to be successful. These essential issues will require consideration as a comprehensive maintenance human factors program and error-reporting system are developed and implemented.

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